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Review on heat recovery technologies for building applications

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ABSTRACT

Recently, there is growing demand for energy saving technologies in buildings due to global warming and environmental impact issue. As a result to this, energy-efficient technologies are becoming more popular amongst researchers and designers. In this regards, to fulfil energy conservation demands, researchers have focused on the development of advance heat or energy recovery with energy-efficient ventilation system. The aim of this paper is to review heat or energy recovery technologies for building applications. The reviews were discussed according to the concept and classification of heat or energy recovery based on types and flow arrangement. The developments of these technologies in integrated energy-efficient system such as mechanical and passive ventilation, air conditioning, dehumidification and photovoltaic panel have also been presented.

Contents

1. Introduction

As stated by Perez-Lombard et al. [1] building energy consumption has increased as a result of economic growth, expansion of building sectors and spread of heating, ventilation and air conditioning (HVAC) system. Since buildings have a long life span, lasting for 50 years [2] or more it is therefore, in conserving the energy, strategies to recover energy consumption in building is strictly important. From the reviewed literatures, it can be said that a large amount of energy is lost due to heating, air-conditioning and ventilation, it is thus very important to recover this energy by adopting heat or energy recovery system for building applications. Besides, heat recovery technology also offers an optimal solution: fresh air, better climate control and energy efficiency [3]. Heat recovery in building applications comes into widespread use in some Europe countries, especially in the high latitude nations such as Germany and Sweden [4,5]. Acknowledgement is worthwhile to new regulatory, policies, standards and energy-efficient technologies development on this field for the last decades, the heat recovery system has currently become a requirement in building designs.

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Nomenclature

BiPV	building integrated photovoltaic
CFD	computational fluid dynamics
ERV	energy recovery ventilator
HRV	heat recovery ventilator
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
NTU	number of transfer unit
PCMs	phase change materials
PVT	photovoltaic thermal

For instance, in Germany, the building code for the year 2000 contains prescripts for well insulated and tight buildings so the energy demand for heating from ventilation air tends to reach about 60% of the total annual energy demand for the building [6]. Using heat recovery it has been shown that the final energy consumption can be reduced up to 20% in cold climates [5]. While in China, more and more commercial buildings and single-family houses use air-to-air heat recovery ventilator as energy saving units for recovering heat from the exhaust air in ventilation systems in the current years [7].

2. Definition and concept

Heat recovery term is referring to an air-to-air heat or energy recovery system which is defined as the process of recovering energy (heat/mass) from a stream at a high temperature to a low temperature stream that is effective and economical to run [8]. On the other hand, Shurcliff [9] defines that heat or energy recovery is any device that removes in terms of extracts, recovers or salvages heat or mass from one air stream and transfers it to another air stream. This means that the energy that would otherwise be lost is used to heat the incoming air, helping to maintain a comfortable temperature. While in industries, it is abbreviated as HRV or ERV (heat recovery ventilation) and became a general use within them. There are many different types of heat recovery systems are available for transferring energy from the exhaust air to the supply air or vice versa [5,10,11]. These include sensible heat recovery and enthalpy (sensible and latent) heat recovery [12]. The heat transfer surfaces based in sensible heat recovery can only transfers sensible heat between the makeup and exhaust air, while in the enthalpy recovery, it can transfers both sensible and latent heat (moisture) however, have greater maintenance requirement and costly than sensible heat recovery [4]. Above all, these systems are significantly proved as the most efficient single energy saving method of building in a cold climate.

Heat recovery systems typically recover about 60–95% of the heat in exhaust air and have significantly improved the energy efficiency of buildings. There are a number of possibilities and concepts for heat recovery from exhaust air in ventilation. The concept to be chosen depends on the possibilities for utilizing the recovered energy [13]. Heat recovery systems are utilized to recover a fraction of the energy loss. Besides offering energy saving, this system also gives some advantages such as, reduces heat loss rather than create heat which is relatively to cost effective. This system also gives effective ventilation where open windows are security risk and in windowless room like bathrooms and toilets. It can also operate as ventilation system in summer, by passing the heat transfer system and simply replacing indoor air with fresh outdoor air. While, during winter, it can reduce indoor moisture, as cooler outside air will have lower relative humidity. Heat recovery system certainly would save energy for fresh air treatment and the efficiency of the heat recovery system is often used to calculate the energy saving [14]. The impact of unintentional airflows on the performance of ventilation units with heat recovery is discussed on the basis of single room ventilation units in Manz et al. [15]. It is shown that the unintentional airflows can considerably reduce the performance of ventilation units in terms of efficiency.

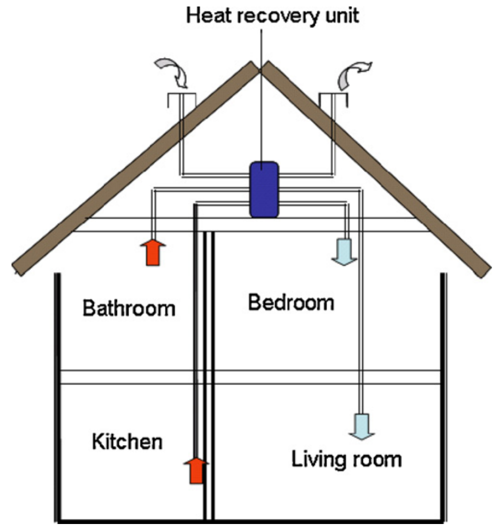

Fig. 1. Heat recovery system.

A typical heat recovery system in building consists of ducts for incoming fresh air and outgoing stale air, a heat exchanger core, where heat or energy is transferred from one stream to the other and two blower fans; one is to exhaust stale air and supply fresh air via the heat exchanger core. Fig. 1 shows a typical heat recovery system installed in ventilation system. In the core, the fresh air stream is automatically preheated or pre-cooled (depending on the season) by the exhausted air and distributed to the interior part of the buildings. The outgoing and incoming air passes next to each other but do not mix in the heat exchanger. They are often installed in a roof space or within the building interior, recover heat from the internal air before it is discharged to the outside and warm the incoming air. In an advance design of this system, sometimes the incoming air is filtered to reduce the incidence of pollen and dust while the outgoing air is filtered to protect the heat exchanger and internal components. This system is also used in building HVAC energy recovery systems, where building exhaust heat is returned to the comfort conditioning system. This device lowers the enthalpy of the building supply during warm weather and raises it during cold weather by transferring energy between the ventilation air supply and exhaust air streams.

Zhou et al. [6] presented a simulation model of heat recovery system based on the new-generation dynamic building energy simulation program called EnergyPlus with the function of heat recovery called ERV in this context to reduce the fresh-air intake load via total heat recovery as shown in Fig. 2.

In order to evaluate the performances of heat recovery system in building ventilation system, Lazzarin and Gasparella [4], discussed a technical and economical analysis to illustrate the possibility of using this system even for small ventilation flow rates. Fehrm et al. [5] gave a review on the development and economics of the technique of heat recovery in Sweden and Germany. In addition, Routlet et al. [14] presented a theoretical analysis of real energy with air handling units and recommended for the heat recovery choice with the experimental data.

3. Types of heat recovery for building applications

Generally, these systems can be categorised according to their applications which are process to process, process to comfort and

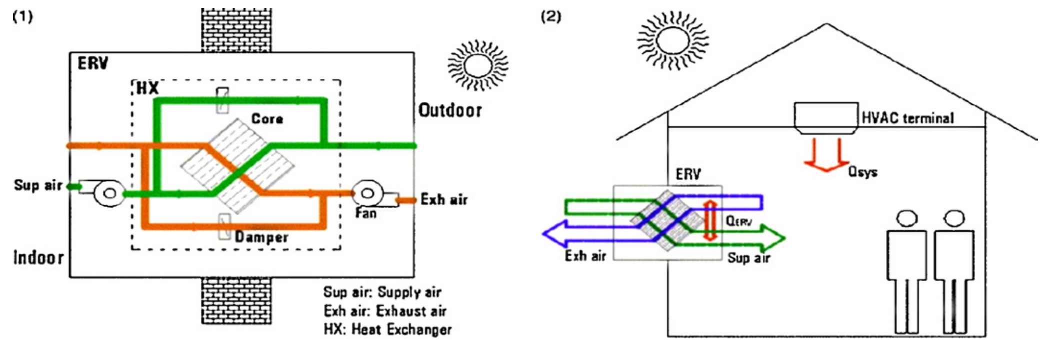

Fig. 2. Structure (1) and air energy-flow (2) schematic diagram of ERV.

Source: [6].

comfort to comfort. In process-to-process system, heat is captured from the process exhaust stream and transferred to the process exhaust stream and transferred to the process supply air stream. Equipment is available to handle high temperatures level. These devices generally recovers sensible heat and do not transfer latent heat. Whist, in process-to-comfort system heat is captured from a process exhaust heats building makeup air during winter. The process-to-comfort devices generally recover sensible heat only. Heat recovery device in comfort-to-comfort lowers the enthalpy of the building supply air during warm weather and raises it during cold winter and this system transfers both sensible and latent energy.

Specifically, heat recovery or air-to-air heat recovery systems are made in so many types, sizes, configurations and flow arrangements. There are many types of heat recovery units which are in use in building applications and these types of heat recovery systems are depending on the heat exchanger core. Shah and Sekulic [16] presented classifications of heat exchangers based on several features: geometry, flow direction, number of different working fluids and so on. Over the last few decades, several types of heat recovery systems such as fixed plate, heat pipe, rotary wheel and run-around coil have been used to recover energy between the supply and exhaust airflows. The following discussion considers the classification based on construction type of heat exchanger which is the heart of heat recovery system.

3.1. Fixed-plate

Fixed-plate heat recovery is the most common type of heat recovery device which is obviously named by the construction of its exchanger. In this unit, the plate exchanger surfaces normally are constructed of thin plates that are stacked together or consist of individual solid panel with several internal airstreams (Fig. 3).

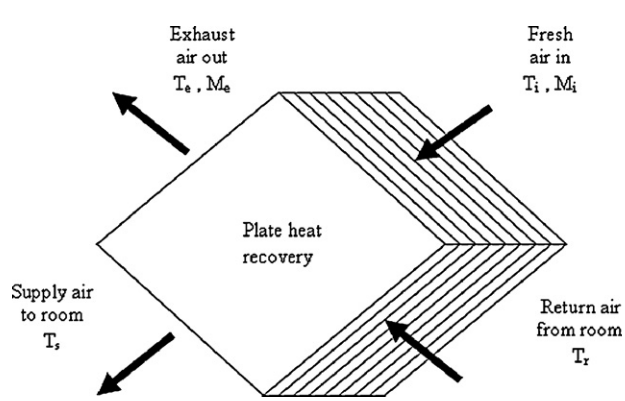

Fig. 3. Fixed-plate heat recovery.

The plates maybe smooth or may have some form of corrugation. It operates by transferring thermal energy from outgoing to incoming air streams via plate heat exchanger surfaces. Figure shows the schematic diagram of heat transfer of fixed-plate. Typical effectiveness of sensible heat transfer is 50–80% and airflow arrangements are counter-flow, cross-flow and parallel flow [17].

Fixed-plate types provide an excellent means of achieving highly efficient heat recovery because their high heat transfer coefficients, coupled with counter-current flow, enable them to produce close end-temperature differences [18]. Han et al. [19] have performed a study to investigate the effect of outdoor weather conditions on the performance of the plate-type heat recovery ventilator. The experiments have been carried out to measure sensible, latent and enthalpy efficiencies by varying outdoor temperature and humidity conditions with the indoor conditions fixed at the standard heating or cooling conditions. They have introduced the coefficient of energy to quantify recovered energy in comparison with the electric power consumption. As a result, they have found that temperature exchange efficiency under winter conditions shows larger values than in summer conditions due to the heat generation by an internal fan.

On the other hand, experiments were conducted by Persily [20]) to test the effectiveness of a cross-flow heat recovery which was constructed of plates and fins made from treated paper capable of moisture transfer. The heat recovery efficiency was determined by comparing the actual heat loss to that expected due to the mechanically induced ventilation and he had found that the exchanger (core of heat recovery) recovered 55–60% of the heat contained in the outgoing airflow depending on the fan speed. In another study, Zhang and Jiang [21] conducted an experimental investigation of the performance of rectangular cross-flow fixed-plate made of membrane to study the heat transferred to recover energy in air conditioning system. They have developed a numerical model and validated the data against the experimental results and found that the highest heat transfer occurred near the inlet area. In accordance to this study, Niu and Zhang [22] investigated a similar study of a square shaped of fixed-plate made of the same membrane and found that the temperature in a cross flow heat exchanger configuration are more evenly distributed in comparison with Zhang and Jiang [21] results.

With the motivation of fixed-plate made of membrane results, Nasif et al. [23] then have came out with a thermal performance of a fixed plate utilized a porous membrane as the heat and moisture transfer surface that can recover both sensible and latent energy with new developed Z-flow configuration as shown in Fig. 4. The effectiveness was found to approximately 75% for sensible and 60% for latent.

In another study, Min and Su [24] have carried out a performance analysis of a fixed-plate called membrane-based energy recovery ventilator as shown in Fig. 5 in order to investigate the effects of

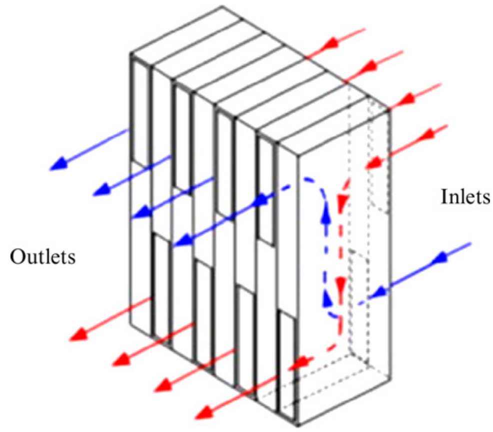

Fig. 4. Z-flow fixed plate utilized a porous membrane as the heat and moisture transfer surface.
Source: [23].

the membrane spacing (channel height) and membrane thickness on the ventilator performance under equal fan power conditions. The results found that for a fixed fan power, as the channel height increased, the total heat transfer rate initially increased.

Recently, more options of fixed-plate material are introduced as the market growth. In regard to this, Lu et al. [25] have developed and investigated the performance of a plastic film plate heat recovery ventilator that works under cross-flow mode by both simulation and experiment. The results indicated that the thin film vibrated when airflow passed through the channels which enhanced heat exchange performance. In addition, the effectiveness of the heat recovery varies from 65 to 85% with airflow rate and the pressure drop is less than 20 Pa. On the other hand, Fernandez-Seara et al. [26] have conducted the experimental analysis of an air-to-air heat recovery unit equipped with fixed-plate heat exchanger made of a sensible polymer for balanced ventilation systems in residential buildings as shown in Fig. 6. Results showed that relative humidity decreased from 95% to around 34%, the heat transfer rate were 672 W and 80% of thermal efficiency.

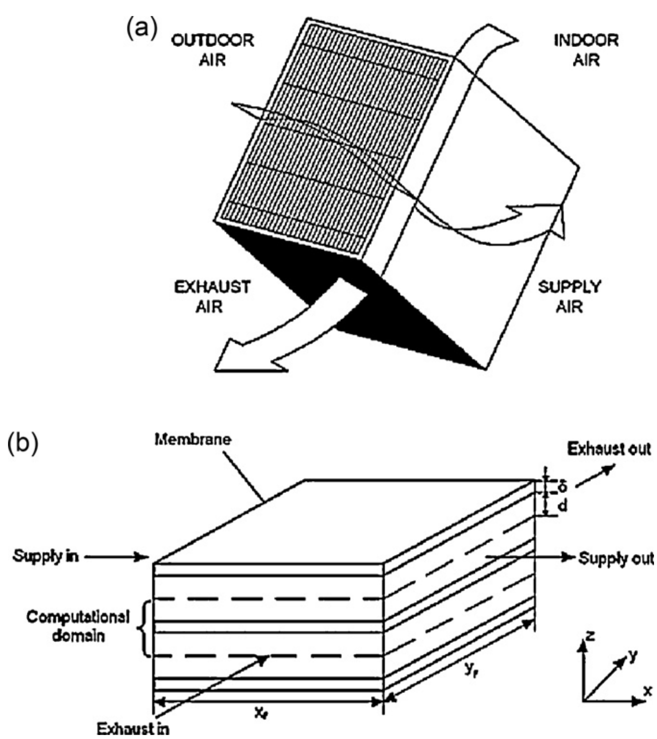

Fig. 5. (a) The core of a typical membrane-based energy recovery ventilator. (b) Physical model.
Source: [24].

3.2. Heat pipe

Heat pipe recovery is a sealed self-contained, fluid evaporating condensing system (Fig. 7). It is a heat transfer device in which the latent heat of vaporization is utilized to transfer heat over a long distance with a corresponding small temperature difference [27]. The unit is divided into two sections for heat/energy exchanges between exhausts and supply air which are evaporator and condenser. Heat is transferred from hot incoming gas to the evaporator section of the heat pipe. Thermal efficiency of heat pipes is between 45% and 55%. There are some advantages in term of flow resistance, such as no moving parts, no external power requirements and so high reliability, no cross contamination, compact and suitable for all temperature application in heating, ventilation and air-conditioning, fully reversible and easy for cleaning. In addition, large quantities of heat can be transported through a small cross-sectional area over a considerable distance with no additional power input to the system [28].

Heat pipe recovery units are suitable to use in naturally ventilated buildings because of they offer several advantages over conventional heat recovery device [13]. They have conducted a performance study of heat pipe recovery system in naturally ventilated building and found that the efficiency of 50% was achieved with the pressure loss about 1 Pa. In another study, Gan and Riffat [29] have investigated the performance of different heat pipe recovery units by experimental measurements and evaluate the pressure loss characteristics using CFD modelling in a two-zone chamber for naturally ventilated buildings. It has been found that the effectiveness decreased with increasing velocity and poor thermal contact between fins and pipes drastically reduces the effectiveness of heat-pipe recovery unit. The numerical modelling indicated that at low velocities the pressure loss coefficient in heat pipe recovery unit decreases with increasing air velocity but the total pressure loss increase with the velocity.

On the other hand, Shao et al. [3] have conducted a study of pressure loss and heat recovery efficiency of heat pipe units using experimental and computational approaches. The results found that heat recovery efficiency of close to 50% have been achieved for a single bank plain-fin unit and for a double bank unit was 40% higher with the pressure loss coefficient reduced as velocity increased. On the other hand, Yau [30] has conducted a theoretical study to investigate the overall effectiveness of heat pipe exchangers operating in naturally ventilated tropical buildings based on NTU method. Heat pipes are also suitable for energy recovery in air conditioning system in tropical countries where incoming fresh air at high ambient temperature could be pre-cooled by the cold exhaust air stream before it enters the refrigeration equipment [31]. El-Baky and Mohamed [10] have carried out a study to investigate the thermal performance and effectiveness of heat pipe for heat recovery in air conditioning applications by measuring the temperature difference of fresh warm and return cold air through the evaporator and condenser site as illustrates in Fig. 8. The results shown that the effectiveness and heat transfer for both evaporator and condenser sections have increased to about 48%. The temperatures change of fresh and return air was increased with the increasing of inlet temperature of fresh air.

With the growing climate change and the thermal comfort issue in tropical hot and humid regions such as Malaysia and other South East Asian countries, heat pipe recovery has taken its place in dehumidification system. Yau [32] has conducted a baseline performance characteristic study of heat pipe in dehumidification system

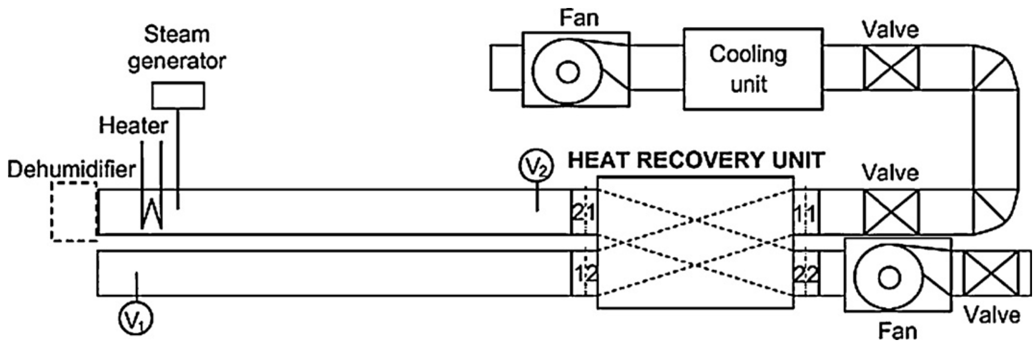

Fig. 6. Layout of the experimental facility.

Source: [26].

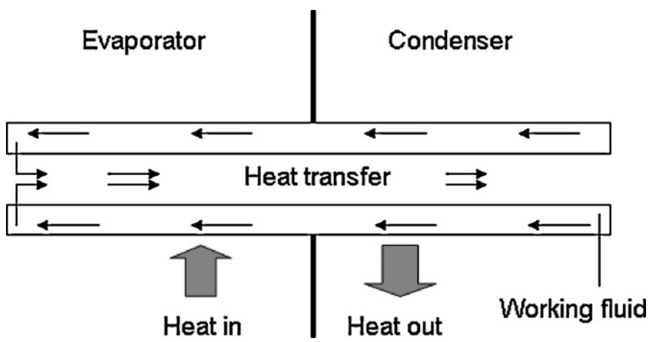

Fig. 7. Heat pipe.

for tropical climates as shown in Fig. 9. By good results obtained, he has recommended that HVAC system in tropical climates should installed heat pipe in their dehumidification systems.

In addition, heat pipe are also widely used in heat recovery systems in domestic appliances such as dishwasher, air conditioner or freezer. In regard to this, Lin et al. [33] provided a thermal model for simulating the performance of a heat pipe system for recovering waste heat in the drying cycle in a domestic appliance as presented in Fig. 10. The results showed that the utilization of heat pipe recovery in the drying cycle of domestic appliances might lead to a significant energy saving in the domestic sector.

3.3. Rotary wheel

Rotary wheel recovery consists of a rotor with permeable storage mass fitted in a casing which operates intermittently between a hot and cold fluid (Fig. 11). The rotor is driven by a motor so that the exhaust air and fresh air are alternately passed through each section. Rotor speed is normally relatively low and in a range of 3-15 rpm. A unique advantage of rotary wheels is the capability of recovering both sensible and latent heat.

Rotary wheels are widely used and the units are known for their high efficiency and trouble-free operation. Temperature efficiencies above 80% are not uncommon. Researches on this field keep active in recent years and involve many theoretical and experimental aspects of rotary wheel recovery for building applications [34]. One of the earliest investigations of rotary wheel recovery was performed by Sauer and Howell [35]. They used the AXCESS energy analysis computer program to evaluate the energy requirements of a two-story office building located in St. Louis on an hour-by-hour basis for a full year using local weather data. Their results showed

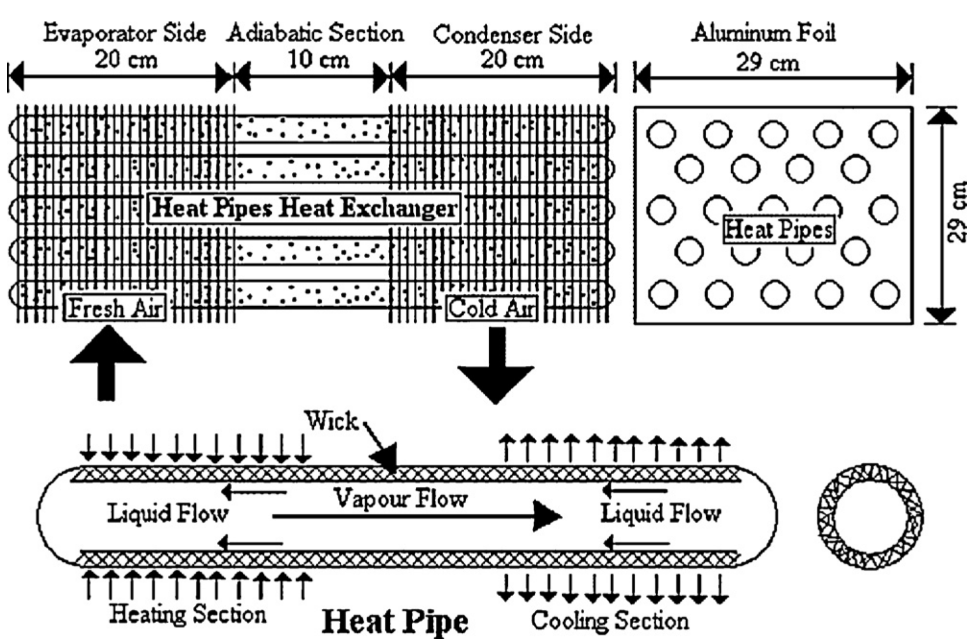

Fig. 8. Heat pipe recovery in air conditioning system.

Source: [10].

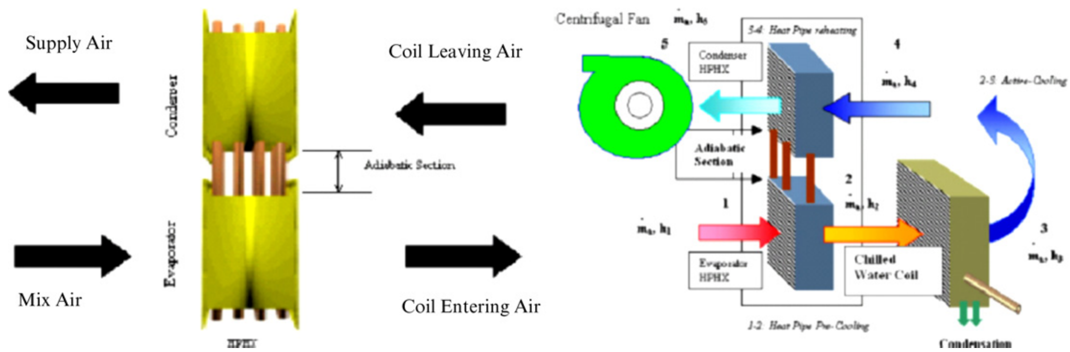

Fig. 9. Heat pipe in HVAC system for tropical climates.

Source: [32].

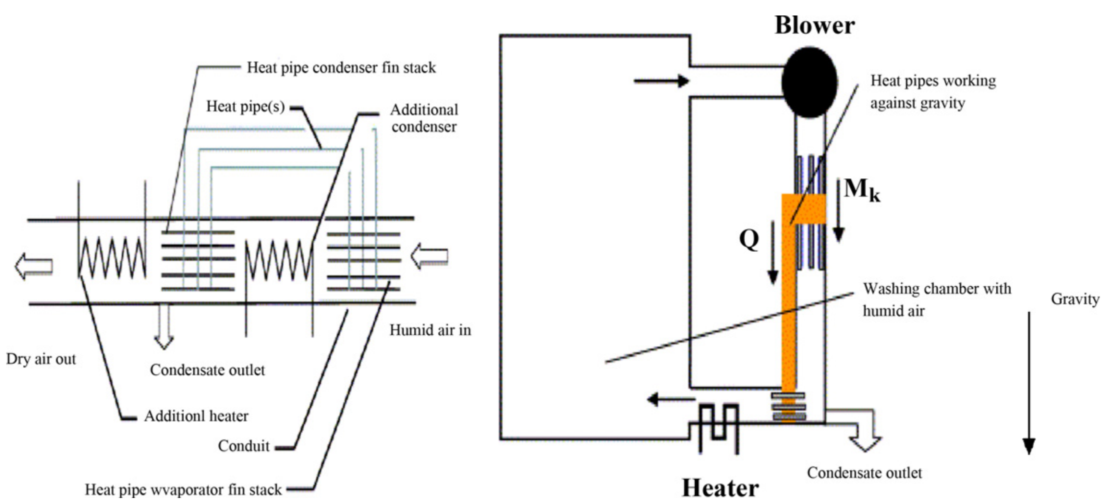

Fig. 10. Heat recovery system using heat pipe solution in drying cycle.

Source: [33].

that energy recovered by the rotary wheel was around 2.5 times greater that the heat recovered by a sensible heat exchanger. By looking to its mechanism, rotary wheel transfers energy from an exhaust to a supply air. The rotary wheel spans two adjacent ducts. One duct carries the exhaust air; the other carries the incoming air, which is to be heated. It also transfers moisture as well as sensible energy between air streams depending on the type of matrix. Rotary wheel was proven as one of the most efficient solution to handle the moisture carried by the ventilation air as to dump the excess moisture within the fresh air supply back to the atmosphere [36].

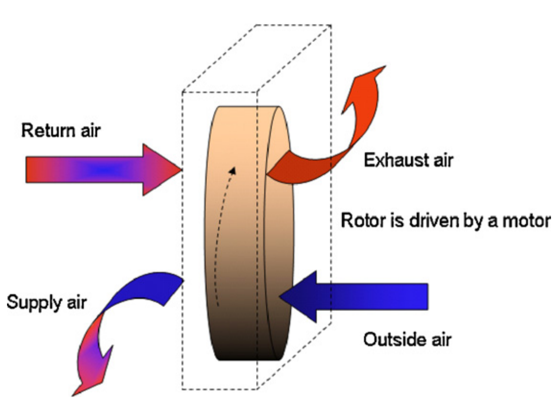

Fig. 11. Rotary wheel recovery.

In regard to this, Nobrega and Brum [37] developed a modelling and simulation to describe the heat and mass transfer in rotary wheel which was validated by comparing the work with independently obtained results. The results showed that heat wheels can be far less efficient than enthalpy recovery wheels depending on the atmospheric conditions. In addition, in rotary wheel system, airflow arrangement is usually counter-flow and increases with rotation speed. Ghodsipour and Sadrameli [38]) estimated maximum effectiveness as a function of rotational speed and hot/cold air velocities. In another study, Simonson and Besant [39], [40] have presented the effectiveness correlations to predict sensible, latent and total effectiveness.

For balanced ventilation systems, the recovered heat power can be at the same rate. Unfortunately, the disadvantage of the rotary wheel is the greater cross-contamination between exhaust and fresh supply air. Due to the rotation device, there will always be a direct and indirect connection between exhaust and fresh supply air. Cross contamination through rotary heat recovery units comes from two mechanisms which are leakage and carryover. In conjunction to this, Hemzal [41] has carried out a performance study of rotary wheel and found that the penetration of airflow (leakage) through the untightness were connected with transfer of contaminants and by the heat which influenced the efficiency. With the encouraging previous results in its efficiency, some researches made intensive studies on the optimal operation of rotary wheel recovery. Dallaire et al. [42] have portrayed a conceptual optimization of rotary wheel with a numerical model where internal

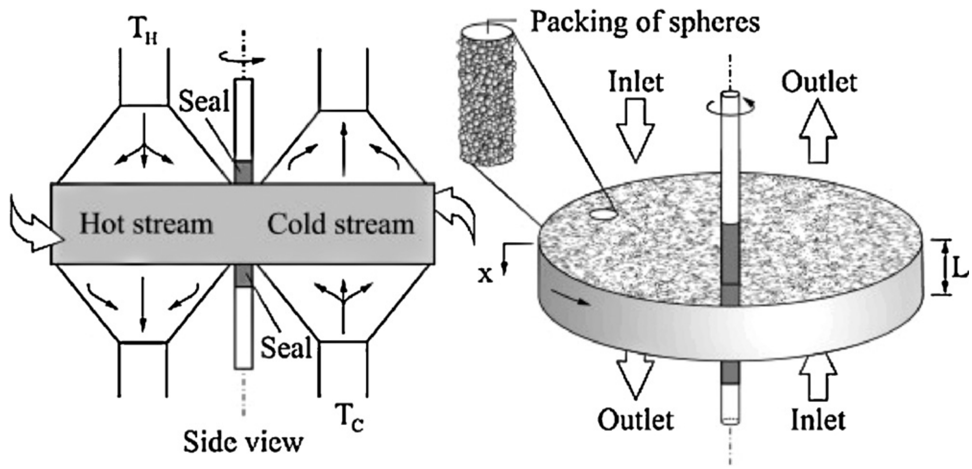

Fig. 12. Schematic representation of the rotary wheel.

Source: [42].

structure was a porous medium in their research. The schematic presentation of the rotary wheel studied is shown in Fig. 12. The numerical results showed that the figure of merit was substantially affected by both design variables and that optimal value of length and porosity could be obtained. On the other hand, San and Hsiau [43]) discussed the effects of NTU and Bi numbers on the performance with one dimensional model that included the axial heat and mass resistance. On the other hand, Abe et al. [44], [45] have presented the analytical model for predicting the effectiveness of rotating air-to-air energy wheels using the characteristic measured on the same non-rotating wheels exposed to a step change in temperature and humidity. Nowadays, with the ability to recover both sensible and latent heat, rotary wheels have been used as desiccant wheels for humidity treatment for dehumidification [46], [47] and enthalpy recovery [35,39,40].

3.4. Run-around

Run-around heat recovery system is the name given to a linking of two recuperative heat exchangers by a third fluid which exchanges heat with each fluid in turn as shown diagrammatically in Fig. 13. Run-around heat recovery use two physically separated heat exchangers (coils) in the air supply and exhaust ducts to recover and transfer heat between them. This system may require an expansion tank to accommodate expansion and contraction of heat transfer fluid. Unlike other heat recovery devices, the run-around system does not require the supply and exhaust air ducts to be located side by side. This gives run-around system an advantage over other available system when cross contamination is a concern [48].

The heat is transferred from the exhaust to supply air using an intermediate heat transfer fluids such as water. The main advantage of this system is that supply and extract duct can be physically separated, even in different part of the building. This provides maximum possible flexibility, as well as no possibility of cross contamination between air streams. The main disadvantages of this system is that because an intermediate fluid is used as a heat transfer medium, the system's efficiency is reduced and electricity is required for pumping fluid. However, pumping liquids remain significantly less energy-intensive than moving air with fans. Thermal efficiency of this type is normally from 45% to 65%.

One of the first studies on the run-around heat recovery system was published by London and Kays [49]. It was found that at a constant NTU, the system had its optimum performance when the

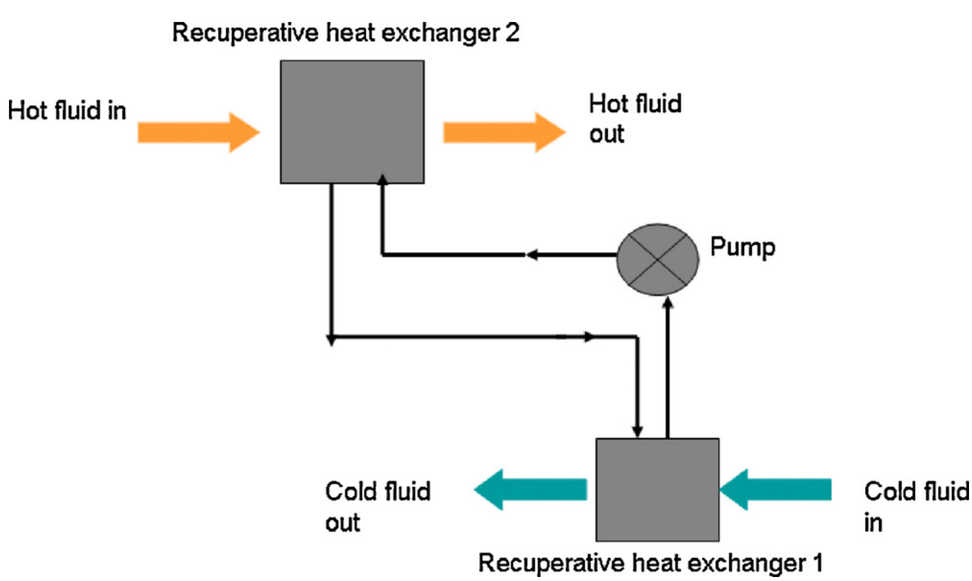

Fig. 13. Run-around system.

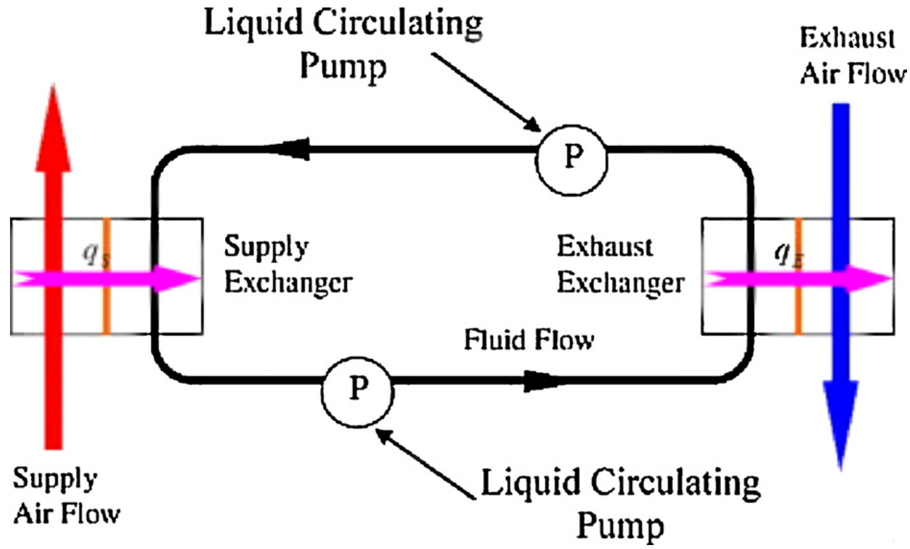

Fig. 14. Schematic diagram of a run-around heat recovery.

Source: [48].

heat capacity rates of the air and coupling liquid were equal. Emerson [50] developed a design of a run-around heat recovery system. He found that the performance of a run-around coil system was sensitive to the rate of circulation of the secondary fluid and that the optimum rate changed with changes in the flow rates of the primary fluids or in the fouling resistances. He also suggested a simple method of monitoring the system to verify that the optimum rate of circulation. Wang [51] has proposed a straight-forward explicit thermal design procedure in his study of run-around heat recovery system. Based on the allowable air pressure drop, the design started with a minimum number of rows and proceeds until all specifications have been met. Hence the smallest possible coil can be obtained by this approach. Forsyth and Besant [52] then developed a numerical simulation to investigate the performance and design of run-around heat recovery with two coil heat exchangers.

On the other hand, Dhital et al. [53] studied the maximum outdoor air ventilation rate and the energy performance of office buildings with and without the run-around heat recovery systems to investigate the energy saving. The results indicated that using a run-around heat recovery system in a building could have significant amount of energy and allow the ventilation airflow rate to be increased without the increasing the energy consumption. Recently, Vali et al. [48] have developed a numerical model to study the heat transfer in a run-around coil heat recovery system with two combinations of counter and cross flow heat exchanger as shown in Fig. 14. The simulated results showed that the effectiveness of each counter/cross flow heat exchanger and overall run-around system were used to develop effectiveness correlation. For a given total surface area of the exchangers, the highest overall sensible effectiveness was achieved with exchangers which have a small exchanger aspect ratio. In another study, Ahmadi et al. [54], [55] have conducted an investigation on transient behaviour of run-around heat and moisture exchanger system.

4. Heat recovery in integrated energy-efficient system for building application

Integrating heat recovery system in energy-efficient system represents significant progress for building applications. The integration of the system leads to a reduction of thermal ventilation losses of the building and to a reduction of the required energy support. This section reviews the previous works of various type heat recovery systems in combination with other low carbon technologies conducted by various researchers.

4.1. Heat recovery in mechanical ventilation system

Since more than 90% of a person's time is spent indoor, therefore it is substantial to maintain the indoor environment within comfortable conditions for the occupants. For this purpose, mechanical ventilation system used in buildings to control indoor air quality and at the same time ventilates the indoor environment. Attempting to improve indoor air quality of buildings, the earliest study of mechanical ventilation system with heat recovery a study has been done in Denmark by using of mechanical ventilation heat pump recovery and the results demonstrated it was beneficial in terms of reduction in mite populations in mattresses and carpets. After that, the study of mechanical ventilation system with heat recovery was conducted by Nazaroff et al. [56]. They have presented a study of mechanical ventilation system with a counter-flow heat recovery in order to determine the effectiveness of this system as an energy-efficient control technique for indoor radon concentration in houses. As a result, they have found that the strategy of building tight houses and the use of mechanical ventilation systems with heat recovery may satisfy energy conservation goals in a cost-effective manner without comprising indoor air quality.

Mechanical ventilation consumes a large amount of electricity for input power and in some cases; it increased a household's electrical power consumption by up to 50% [57]. In respond to this, several researchers have investigated the ability of heat recovery unit coupled in this system to recover the energy loss. In mechanically ventilated buildings, heat recovery from ventilation air is the single most important means of reducing ventilation energy consumption [58]. In regard to these, Nguyen et al. [59] have studied the overall performance of mechanical ventilation heat pump system with heat recovery during forced ventilation. The methods for recovering sensible heat during ventilation process have been evaluated experimentally in four types of ventilation which are type A, B, C and D the results have been compared with the case of none heat recovery ventilation. For type A, no heat recovery is used while in Type B, a separate sensible heat recovery was used. In type C, single heat recovery was used for recovery heat in an integrated heating-ventilation and in type D, double heat recovery was used to recover heat and heat pump as the second heat recovering

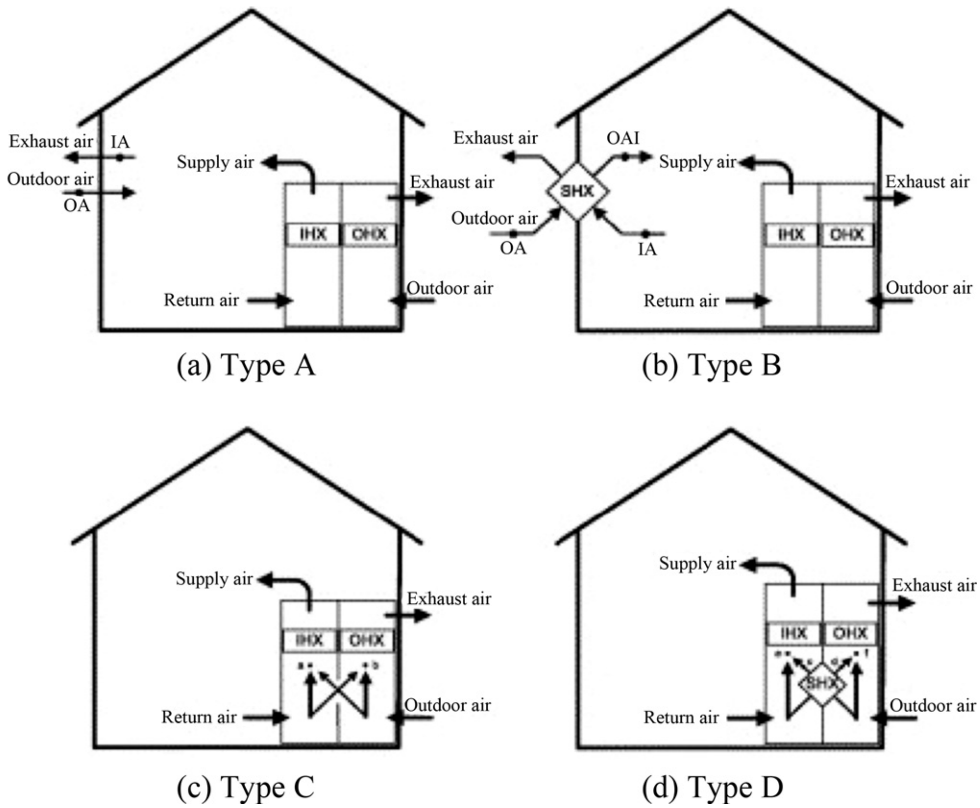

Fig. 15. Mechanical ventilation heat pump system with four types of ventilation heat recovery.

Source: [59].

mechanism as shown in Fig. 15. In this study, it was found that the integrated mechanical double heat recovery pump system is most efficient for saving energy for an indoor space.

It is obviously known in literatures that mechanical ventilation with heat recovery system is efficient to remove pollutants and adequate sufficient ventilation to buildings. An advanced mechanical ventilation heat recovery incorporating heat pump system has been developed by Riffat and Gillott [60] which has a low capital cost and little maintenance as shown in Fig. 16. The results indicated that the air changes per hour complied with the ASHRAE Standard to maintain indoor air quality.

Manz and Huber [57] have presented mechanical ventilation that united two functions: fluid transport and heat recovery. This unit was investigated by means of experiments and simulations. It was shown that using this concept, it was possible to realize a mechanical ventilation unit with high efficiency of heat recovery. In another research, Manz et al. [61] presented performance of single room ventilation units with recuperative or regenerative mechanical ventilation heat recovery by means of experiments and numerical simulations. It was shown that using these units, rooms could be efficiently ventilated at a good level of thermal comfort, temperature efficiencies up to 78% at low levels of electric energy input.

Jokisalo et al. [62] on the other hand, have performed a simulation study using a dynamic thermal modelling of various mechanical supply and exhaust ventilation system incorporating heat recovery in typical Finnish residential apartment building in Finland. The systems studied were based on cost efficient realistic component available in the market. According to this study, energy efficiency in a residential building can be improved remarkably by using this system as the results showed that a traditional exhaust ventilation system can use up to 67% more energy than a heat recovery system having 80% efficiency and 41% more energy that a heat recovery system having 60% energy recovery efficiency. The efficiency of heat recovery has a significant effect on energy consumption as the results showed total annual specific energy consumption at 80% temperature efficiency was 11% less than 60% efficiency.

Mechanical ventilation with heat recovery is often considered as one of the key elements of a low energy residential building in cold winter regions [63]. However, in extremely cold or arctic climates where they have long winter season, it is difficult to obtain a traditional mechanical ventilation heat recovery system to operate as intended due to continuous moisture problems and inlet air below the freezing point. Researchers and designers devote much attention to frost formation and to means of getting rid of the frost. In respond to these problems, Kragh et al. [64] have constructed a novel mechanical ventilation heat recovery with the capability of continuously defrosting itself without using supplementary heating suitable for cold or arctic climates. The experiment's results showed that the heat recovery efficiency is still high and capable to defrost below the freezing point.

4.2. Heat recovery assisted passive ventilation

The term passive in this context indicates the opposite of active or mechanical ventilation where the fresh air is provided by fans or heat pumps. An early attempt in the field of heat recovery for passive or natural ventilation solutions was based on a vertical counter-flow air-to-air heat exchanger and achieved a heat recovery efficiency of 40% [65]. Riffat and Gan [8] have been undertaking a project on heat pipe recovery with solar-assisted natural ventilation in a glazed solar chimney as an integral part of the system with heat recovery efficiency close to 43%. In this study, a heat pipe recovery unit used was a heat exchanger consisting of externally finned sealed pipe containing a volatile fluid such as methanol

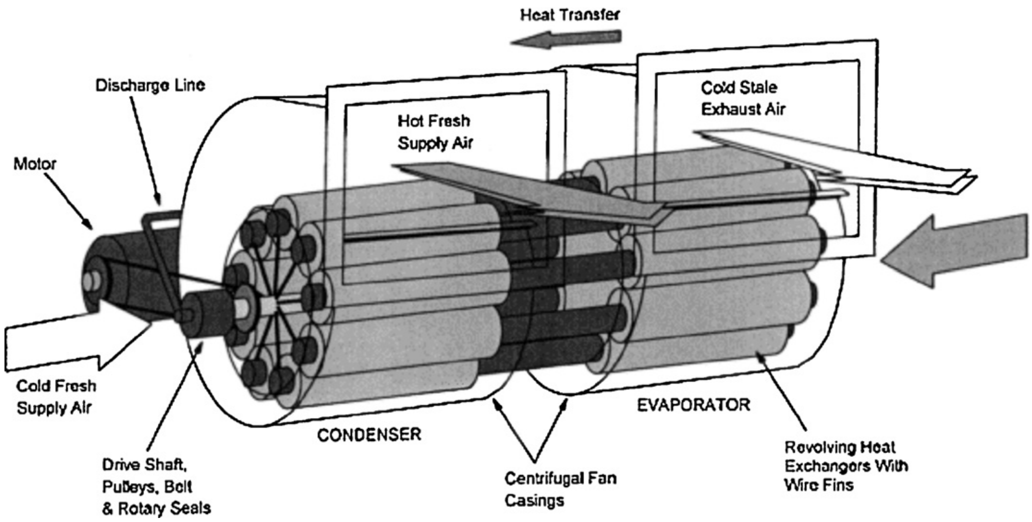

Fig. 16. MVHR heat pump system.

Source: [60].

which has an operating temperature range from -40°- 100 °C as shown in Fig. 17. This unit was divided into evaporator and condenser sections. They have found that installing heat-pipe recovery in the chimney increased the flow rates in naturally ventilated buildings and also decreased the thermal buoyancy effect and thus they have suggested, in order achieving required airflow rates in naturally ventilated buildings with heat recovery, use should be made of wind forces.

Recently, Hviid and Svendsen [66] have presented an analytical and experimental analysis of heat recovery concept that has been developed for passive ventilation systems suitable for temperate climates as shown in Fig. 18. The total pressure loss and temperature exchange efficiency of heat recovery was measured and found to be 0.74 Pa and 75.6%, respectively for a design flow rate of 560L/s.

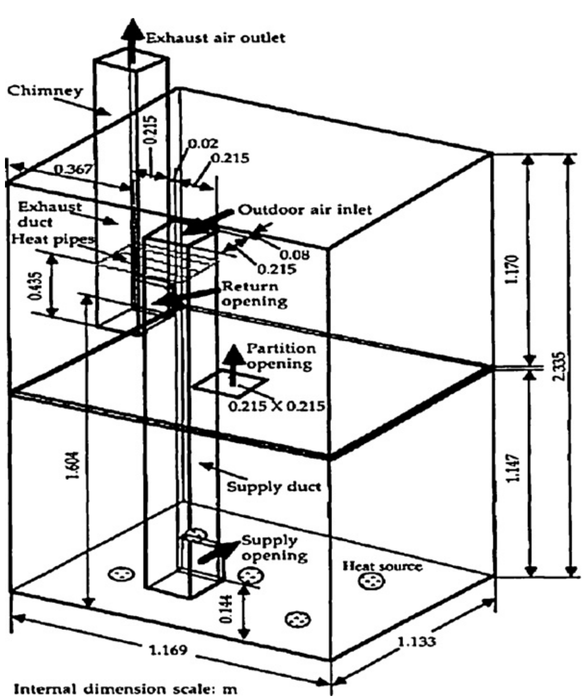

Fig. 17. Schematic diagram of the naturally ventilated room with heat pipe recovery unit.

Source: [8].

4.3. Heat recovery assisted-cooling or air conditioning

Within the buildings, most of energy is for provision of heating, cooling and air conditioning [67]. It is observed that plentiful waste condensing heat from traditional air conditioning system is directly exhausted to the environment, especially in summer time when the system operates on air conditioning mode [68]. Many methods have been attempted to tackle these problems. In regard to this, several researchers tried to add a heat recovery system on the air conditioning systems [69]. In a conventional air conditioning system, the humidity is controlled by cooling the supply air stream below its dew point temperature. The cold air is then reheated to a temperature that is suitable for the conditioned space. The earliest study reported by Yau and Ahmadzadehtalatapeh [27] declared that the application of heat recovery unit of heat pipe type in the conventional air conditioning system could be an efficient technique to control humidity and reduce the amount of heat energy required. Recently, El-Baky and Mohamed [10] also stated that by the application of the heat pipe recovery between two streams of

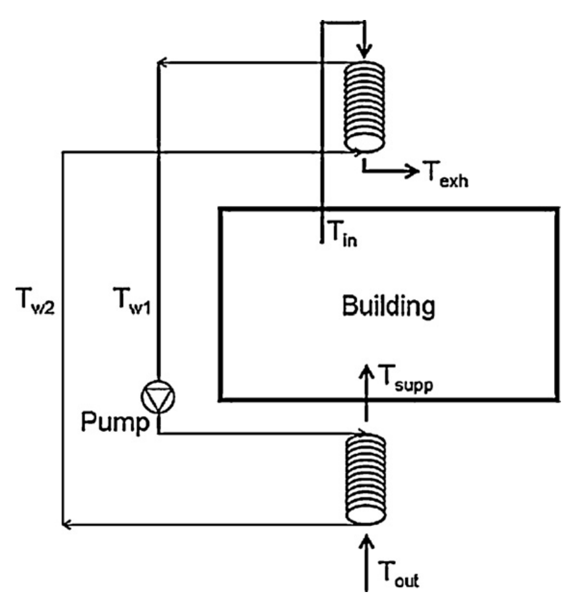

Fig. 18. Schematic of the heat recovery concept.

Source: [66].

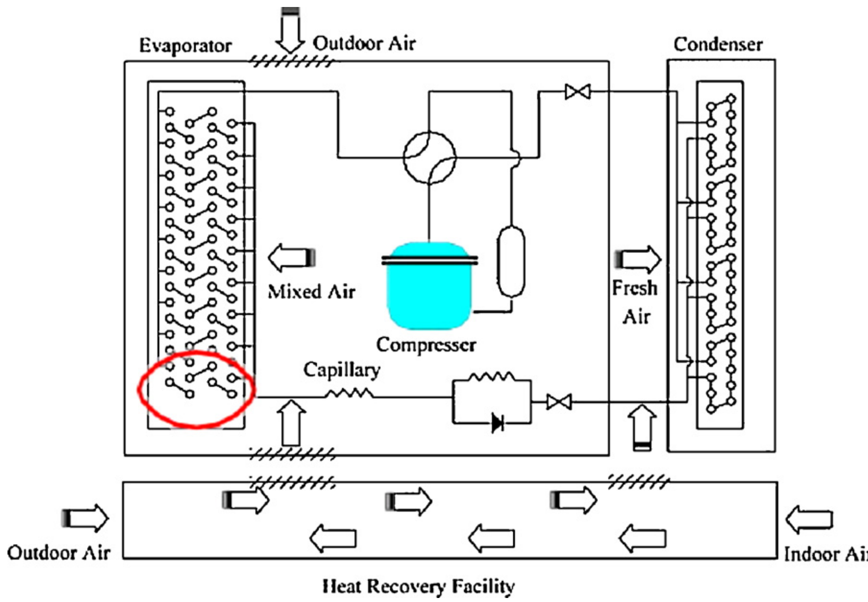

Fig. 19. Schematic diagram of the window-type air conditioner with heat recovery facility.

Source: [70].

fresh and return air in an air conditioning system, the incoming fresh air could be cooled down.

On the other hand, Zhang and Jiang [21] have presented a detailed heat and mass transfer model for an energy recovery ventilator with a porous hydrophilic membrane core to increase the efficiency of the air conditioning system. It is found that the sensible heat exchange, moisture exchange and the enthalpy exchange was promising. A study of window-type air conditioner with heat recovery system has been investigated by Liu et al. [70]) as shown in Fig. 19. With the heat recovery system, they have found that the temperature of the mixed air would increase while in terms of relative humidity, would depend on the properties of the indoor air and outdoor air and their ratios. Gu et al. [71] have developed a heat recovery system using phase change materials (PCMs) to store rejected (sensible and condensation) heat from air conditioning system. A new heat recovery technique for air conditioning system was then proposed by Gong et al. [68] employing a compound air-cooling and water cooling condensing module to replace the traditional sole air-cooling condensing module. This proposed system was found had the ability to improve cooling and heating effects and recover condensing heat for heating sanitary water.

A heat recovery unit was installed in study of central forced-air heating and cooling system to control indoor air quality (IAQ) conducted by Persily [20] in residential buildings. In this study, the heat recovery ventilator withdrew air from the return side of the forced-air system and replaced it with outdoor air drawn through the heat exchanger. The actual outdoor airflow rate during operation was selected to provide an air change rate of 0.35 h^{-1} through heat recovery system. The outcome of this study stated that the tight Miami houses met the ASHRAE minimum air change rate on the hot day but still far short on the cold days.

In another study, Martinez et al. [72] have designed a mixed-air heat recovery system, consisting of two heat pipes and indirect evaporative recuperators for air conditioning whereas the energy characterization of the mixed heat recovery system was performed by means of experimental design techniques. In their study, they have analysed the influence of temperature, flow, relative humidity, and water flow on the basic characteristics defined by the mixed system. The results found that by application of the mixed heat recovery system in the air conditioning system installations consisting of two heat pipes and indirect evaporative systems, part of the energy from the return airflow could be recovered, thus improving energy efficiency. They also found that the heat recovery factors show a lineal dependence in relation to temperature and outdoor airflow factors.

Nasif et al. [23] have performed experiments on thermal performance of an enthalpy heat exchanger as the heat and moisture transfer surface for air conditioning energy recovery systems as shown in Fig. 20. It has been shown that in humid climate a saving of up to 8% in annual energy consumption can be achieved when this enthalpy exchanger used as a heat recovery instead of a conventional air conditioning system. Mahmud et al. [73] have done a performance testing of a run-around heat recovery system for air conditioning which could transfer sensible and latent energy with non-adjacent ducting as shown in Fig. 21.

4.4. Heat recovery combined with dehumidification system

Due to the scarcity of conventional air dehumidification system, many efforts have been made since decades ago. With the demands of energy conservation in dehumidification system recently, Zhang et al. [74] have proposed a fresh air processor with liquid desiccant total heat recovery in order to improve indoor air quality and decrease the energy consumption of the air conditioning system. In another research, Zhang [75] has proposed four independent air dehumidification systems with heat recovery strategies. These systems were compared with a mechanical dehumidification system with no heat recovery. The results showed that the system of mechanical dehumidification with membrane total heat recovery consumes the least primary energy. Recently, a performance study involving modelling and experimental of air dehumidification system combined with membrane-based total heat recovery study was carried out by Liang et al. [76], [77] in order to improve the efficiency of a conventional dehumidification system in hot and humid regions as shown in Fig. 22. The results indicated that as compared to conventional dehumidification system, the air dehumidification rate (ADR) of the new developed system is 0.5 higher and it has the ability to perform well under harsh hot and humid weather conditions.

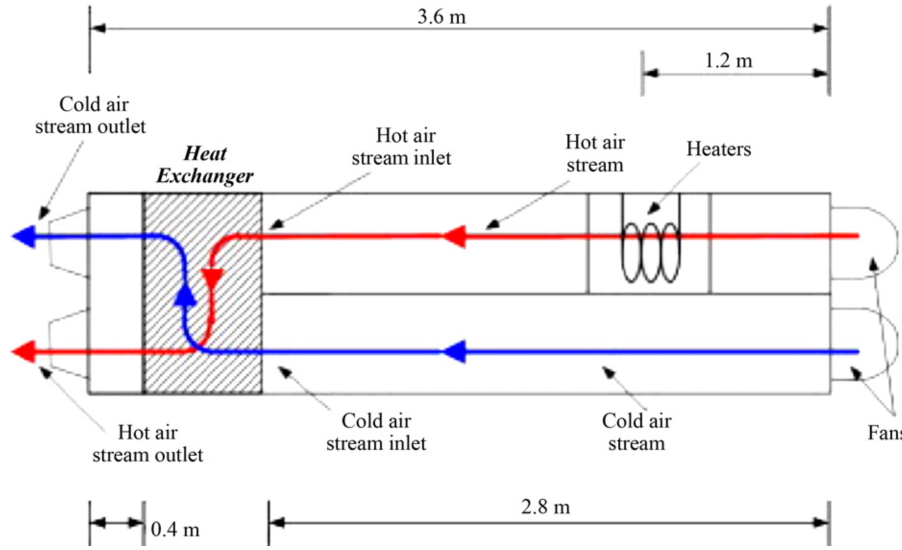

Fig. 20. Heat and mass recovery system in air conditioning.

Source: [23].

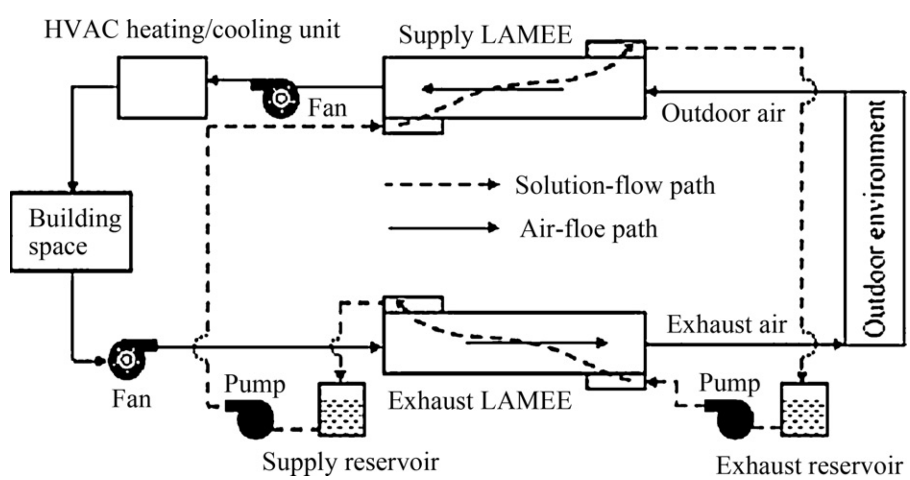

Fig. 21. Schematic of a run-around heat recovery system in a air conditioning.

Source: [73].

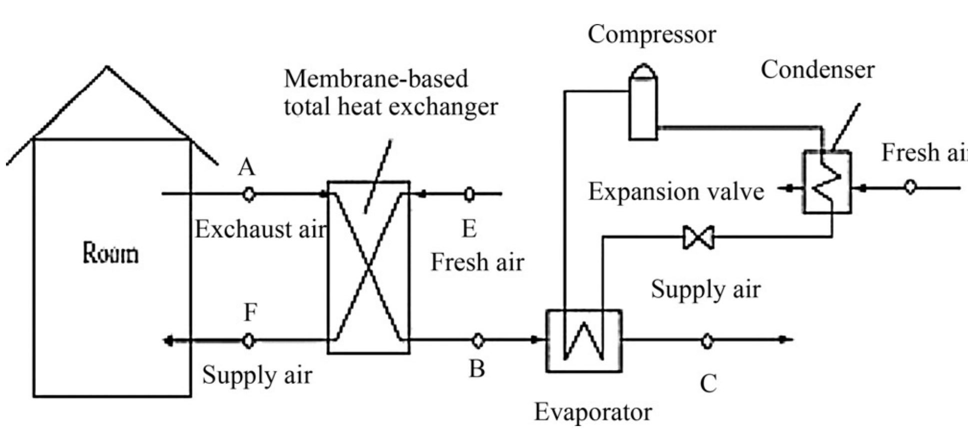

Fig. 22. Schematic of air dehumidification system combined with membrane-based total heat recovery.

Source: [76].

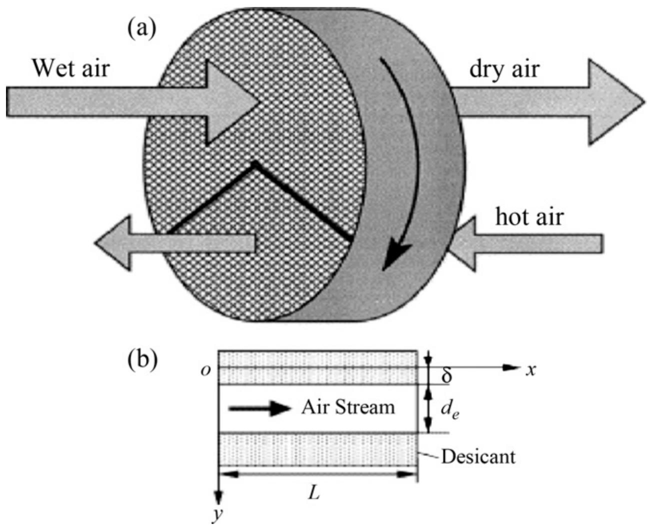

Fig. 23. Schematic of the rotary desiccant wheel for dehumidification and enthalpy recovery.
Source: [78].

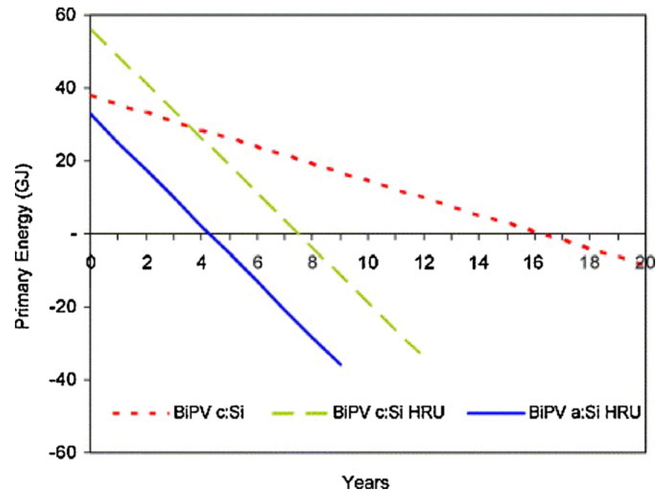

Fig. 25. BiPV with heat recovery energy payback periods.
Source: [81].

Zhang and Niu [78] in their paper presented the performance of rotary wheel so-called desiccant wheel for air dehumidification and enthalpy recovery as illustrated in Fig. 23. Effects of rotary speed, number of transfer units and the specific area on the performance of the wheel were investigated and compared.

Liu et al. [70] have combined a rotary wheel heat recovery with rotary desiccant wheel in a dehumidification system as shown in Fig. 24 to analysis its energy consumption. The results showed that, compared to conventional system, energy savings were possible to be gained.

4.5. Heat recovery coupled with photovoltaic/solar panel

Heat recovery coupled with photovoltaic/solar panel is an advanced energy-efficient system which is developed is developed in accordance to the weakness of solar panel when exposed to high temperature which resulting low efficiency. Maffezzoni et al. [79] has stated that the presence of cooling interface improves the electrical efficiency of the solar cell and in addition increase the lifetime of the system. Thus, heat recovery unit in this system works to cool the photovoltaic panels while providing a heat source for the occupants. Only few researches have been performed in the integration of heat recovery system with photovoltaic panel. Bazilian and Prasad [80] have conducted a modelling study of a photovoltaic heat recovery system for buildings professional and validating with experimental data. The results indicated that the model helped to stimulate of a modular heat recovery unit addition to a building integrated photovoltaic system and could be customised to appropriately meet the needs of the users. On the other hand, Crawford et al. [81] have presented the results of a life-cycle energy analysis of a building integrated photovoltaic system with heat recovery unit. The thermal output from heat recovery units was calculated by adding the thermal and electrical output for each system and subtracting the fan energy use. They have found that the energy pack periods between 4 and 16.5 years was obtained with BiPV with heat recovery has the highest embodied energy for all three systems as shown in Fig. 25.

Recently, a study of condenser heat recovery with a PVT air heating collector has been conducted by Sukamongkol et al. [82] as shown in Fig. 26. They have carried out an experimental test to investigate the validity of developed simulation model in predicting the dynamic performance of condenser heat recovery and found that the model agree satisfactorily with the results observed in experiments. This system can save energy by approximately 18% with the use of a photovoltaic thermal combined with the heat recovered from the condenser.

Another modelling and simulation of a hybrid photovoltaic module equipped with a heat recovery system was carried out by Maffezzoni et al. [79]. Using the numerical model, he investigated the effects of temperature profile along the photovoltaic cells and the analysis of the model can be used to predict the current voltage levels that can be sustained by the solar panel. However, many aspects still need further investigations to include the direct heat

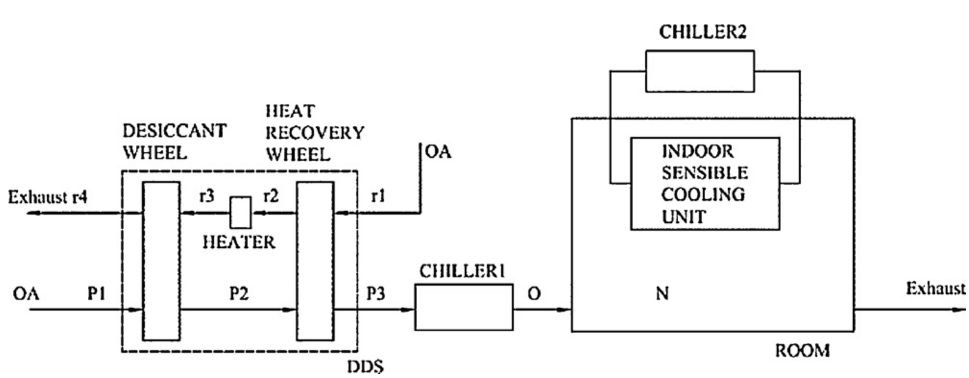

Fig. 24. Schematic a rotary wheel heat recovery with rotary desiccant wheel in a dehumidification system.
Source: [70].

Table 1
Heat recovery types, efficiency and advantages.

Types of heat recovery	Typical efficiency	Advantages
Fixed-plate	50–80%	Compact, highly efficient due to high heat transfer coefficient, no cross contamination, can be coupled with counter-current flow which enabling to produce close en-temperature differences
Heat pipe	45–55%	No moving parts, no external power requirements, high reliability, no cross contamination, compact, suitable for naturally ventilated building, fully reversible, easy cleaning
Rotary wheel	Above 80%	High efficiency, capability of recovering sensible and latent heat
Run-around	45–65%	Does not require the supply and exhaust air ducts to be located side by side, supply and exhaust duct can be physically separated, no cross contamination

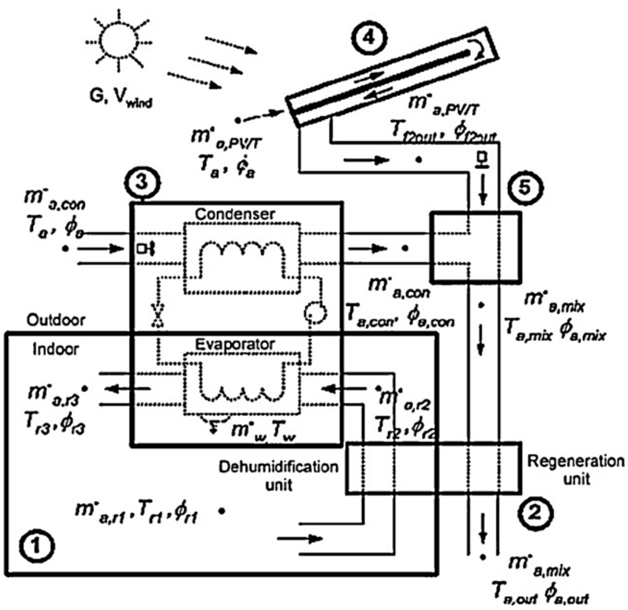

Fig. 26. Schematic diagram of a condenser heat recovery with a hybrid photovoltaic/thermal.
Source: [82].

exchange between the lower face of the photovoltaic cell and the air within the collector.

5. Conclusions

Findings from literature review shown that there are different of heat recovery types in the market nowadays such as fixed plate, heat pipe, and rotary wheel and run-around units utilized to recover energy loss. Table 1 summarized their efficiency and advantages.

Throughout the literatures, it is found many works have been done since 1980s' in relation to heat recovery systems. In the past, the works had emphasized more on heat or mass transfer in heat exchanger until the buildings standards are introduced then the efficiency and performance of heat recovery in building applications such as ventilation, air conditioning and dehumidification systems come into concerns. For natural or passive ventilation heat pipe recovery has been used since no moving part is required in this system. For mechanical ventilation, researchers tend to integrate heat pump so-called mechanical ventilation heat pump recovery while rotary wheel recovery has widely been used in desiccant dehumidification to recover heat and moisture. On the other hand, many theoretical and experimental works in literature has been conducted for integration heat recovery system with mechanical ventilation, natural ventilation, air conditioning and dehumidification systems. However, combination of heat recovery with low carbon technologies such as evaporative cooling and desiccant dehumidification is just a handful amount and very limited studies have been done to integrate them in one system. Besides, the integration of heat recovery with photovoltaic panel is still new and only few researches have been found.

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